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DEVELOPMENT AND USE OF AN ANALYTICAL MODEL TO PREDICT THE INELASTIC SEISMIC BEHAVIOR OF SHEAR WALL, REINFORCED CONCRETE BUILDINGS

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SUMMARY

The development of an analytical model to predict the inelastic seismic response of reinforced concrete shear wall buildings, including both the flexural mode and the shear mode of failure, is presented. The use of shear wall buildings is quite common in Chile; their seismic behavior has been successful during past severe earthquakes, both from the serviceability requirements and the prevention of collapse points of view. However, construction practice in recent years has shown a tendency to reduce the amount of walls, with consequences that cannot be optimistic, since researchers that studied the behavior of Chilean buildings during the 1985 earthquake concluded that the amount walls present in most of these buildings was just enough to obtain the very good performance they exhibited. One efficient way to clarify the doubts about the seismic behavior of these buildings is to develop a computer model to predict such a behavior. To achieve this objective a shear mode of failure model based on experimental results has been plugged into a computer program that could already predict the inelastic seismic behavior of buildings associated to the flexural mode of failure of the structural elements, in such a way that a shear or a flexural mode of failure may be predicted by the computer program depending on the relative strength of each wall associated to these modes of failure. The paper discusses the most relevant problems and solutions devised during the development of this model. Preliminary results showing the behavior of buildings as a whole and of individual shear walls are also presented.

INTRODUCTION

Properly designed multistory, reinforced concrete, shear wall buildings should behave in a ductile flexural manner when subjected to severe earthquake ground motions. Nevertheless, there are cases where the flexural mode of failure may not be possible to attain due to the large flexural strength of the walls as compared with its shear strength. This may be the case of structural systems having squat shear walls, or situations where higher modes of vibration may force an undesired shear failure. Several examples of this situation may be found in the behavior of reinforced concrete, shear wall buildings during the March 3, 1985 Chilean earthquake.

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the 1985 earthquake concluded that the amount walls present in most of these buildings was just enough to obtain the very good performance they exhibited [Wood, 1991]. One efficient way to clarify the doubts about the seismic behavior of these buildings is to develop a computer model to predict such a behavior. The availability of this model will also permit a better estimation of both the ultimate lateral strength of the shear wall buildings and the inelastic deformation demand under severe ground motions. The use of this information will help to improve present code procedures to design these buildings.

In order to develop a model to achieve the objective stated above, it has to include the possibility of developing both the flexural and the shear modes of failure in the shear walls. Very few researchers have addressed this problem. Saiidi and Sozen [1979] studied several hysteretic models associated to the flexural mode of failure; in one of them, the pinching effect typical of shear behavior, was included and labeled as the SINA model. Lately, Linde and Bachmann [1994] developed an element to represent the inelastic seismic behavior of shear walls controlled by the flexural mode of failure, with a modest influence of shear cracking. The model developed in this research is based on the LARZ computer program [Saiidi, 1979], which has been modified to allow the walls to develop a shear mode of failure when its lateral strength is smaller than the strength to develop the flexural mode of failure. The shear model characteristics were determined from experimental results obtained from cyclic test of shear walls and beams, as described below.

The paper discusses the most relevant problems and solutions devised during the development of this analytical model. Preliminary results showing the behavior of buildings as a whole and of individual shear walls are also presented. An in-depth study concerning the desirable structural characteristics of shear wall systems in order to obtain an acceptable behavior during severe earthquakes is presently under development.

MODEL FOR FLEXURAL MODE OF FAILURE

This model was taken from the LARZ computer program and is shown in Fig. 1. The envelope curve includes a cracking point C, a yield point Y, a maximum strength point U defined by a maximum concrete compressive strain of ε_{cu}=0.003, and a collapse or maximum curvature point defined by a maximum concrete compressive strain of ε_{cu}=0.01. The hysteresis rules were taken directly from the SINA model [Saiidi and Sozen, 1979]. The bending moment and curvature values were defined using the standard theory for reinforced concrete elements; both the boundary reinforcement and the distributed vertical reinforcement were taken into account when bending moments were evaluated for shear walls. The axial force originated by dead and live loads was included in the calculation of the bending moments for columns and shear walls.

MODEL FOR SHEAR MODE OF FAILURE

This model is shown in Fig. 2 and was developed primarily for squat shear walls having an aspect ratio M/VL_w of 1.0 or smaller, where M is the maximum bending moment present in the wall, V is the shear force and L_w the length of the wall; it was later extended to the case of slender shear walls with aspect ratios larger than 1.0. The model for squat walls is based on the experimental results obtained from the cyclic test of 26 full scale, shear wall specimens, that were designed to exhibit a shear mode of failure [Hidalgo, Jordan and Ledezma, 1998], which allowed to define points C, Y and U of the envelope curve shown in Fig. 2. The actual slope of branch YU obtained from the test was one of decreasing shear strength; nevertheless, this fact produced problems in the software that could not handle a structure with a stiffness matrix that at some points in the time-history response could lose its property of being positive definite. For this reason, the branch YU was taken with nearly constant shear strength, but maintained the ultimate displacement δ_{ult} obtained from the experimental results. Once this displacement is attained in a wall, the element is removed from the structure and the stiffness matrix is re-evaluated. Figure 2 also shows the eight hysteresis rules for this model, that also follow the SINA model; in this case, a crack closing point is defined to account for the pinching effect always present in the hysteretic behavior after a shear crack has developed. The model characteristics for slender shear walls were obtained from test results of reinforced concrete beams [Bresler and Scordelis, 1966; ASCE-ACI, 1973]. This model is similar to that described above, with the only difference that points Y and U shown in Fig. 2 become only one point in the tests of beams when a shear failure is attained.

Figures 3 through 7 show comparisons between experimental results and model envelope curve definitions for both squat and slender shear walls. Figure 3 shows the estimation of drift at first cracking DR_{cr} while Figs. 4 and 5 show the estimations for drift at maximum strength DR_u and at ultimate deformation DR_{ult}. Experimental results for beams may be only obtained for DR_{cr} and DR_u; therefore DR_{ult} was assumed to be 0.014 for walls with aspect ratio larger than unity. Same information as before but for strength are shown in Figs. 6 and 7 for shear strength at cracking V_{cr} and maximum shear strength V_u, respectively. In these cases, different models were adopted for squat and slender shear walls. As far as cracking strength is concerned, the V_c value proposed in the ACI Code [ACI, 1995] showed the best correlation with experimental results; to improve this correlation for walls with aspect ratios equal or less than 1.0, the ACI value for V_c was increased by 12%. Concerning the V_u estimation, the best correlation with experimental results for squat walls was obtained for the contribution of concrete V_c as proposed by Arakawa and the contribution of shear reinforcement as proposed in the ACI Code [Hidalgo, Jordan and Ledezma, 1998]; likewise as before, to improve this correlation the V_u value using the Arakawa model for V_c was increased by 41%. The estimation of V_u for slender walls was taken as the ACI model to predict the shear strength of beams, but using as contribution of concrete the expression proposed by Paulay and Priestley [1992]; this model has been labeled as N.Z. model in Fig. 7. Finally, the value of V_{ult} shown in Fig. 2 was taken as 1.01 times V_u.

RESULTS OF INELASTIC ANALYSES OF BUILDINGS

The model described above was used to predict the inelastic seismic behavior of two real Chilean buildings constructed within the past seven years. Both have shear wall, reinforced concrete structural systems and were subjected to the N10E component of the accelerogram recorded in Llolleo during the March 3, 1985 Chilean earthquake. Building Nº 1 is a 6-story structure, quite regular both in plan and vertically, that has shear wall area to plan area ratios of 0.03 and 0.02 in each of the principal directions. Results for this building are not shown in this paper. Building Nº 2 is a 16-story structure, whose plan is shown in Fig. 8, regular in plan but not vertically. Shear wall area to plan area ratios are 0.018 and 0.02 in the X and Y-directions, respectively. Following results correspond to the response for the earthquake acting in the X-direction; due to the plan regularity of the shear wall distribution, a two-dimensional analysis was used, i.e., no torsional response was included in the analysis. Also, the computer model considered one story for each couple of consecutive stories in the actual building, with a story height equal to twice the actual interstory height. Figure 9 shows the shear cracks and plastic hinge patterns in axes 5 and 9 at t = 32 seconds after the beginning of the ground motion. Figure 10 shows the total base shear as a function of time; total seismic weight of the building was estimated to be 117 KN, so that maximum base shear is 22% of total weight. Overall predicted response for this building indicates that 43% of the shear walls would develop shear cracks, with a maximum interstory drift of 0.01 at the upper stories. Figures 11 and 12 show the hysteresis loops developed in wall M1, shown in Fig. 9, both for the shear behavior and the flexural behavior, respectively. It can be observed from Fig. 11 that shear behavior went beyond the cracking point in the lower stories, but maximum shear strength V_u of the walls was not reached; for this reason, energy dissipated through shear behavior was rather limited. On the other hand, the formation of a plastic hinge in both senses of the earthquake action is apparent from Fig. 12, with larger energy dissipation through the flexural behavior than through the shear behavior. The instant of time t = 32 seconds has been marked by a full dot in Figs. 10, 11 and 12, to relate element behavior of wall M1 with cracking and plastic hinge patterns shown in Fig. 9.

The computer program capability is presently being verified by comparing its prediction with the actual behavior experienced by three buildings located in Vina del Mar and Valparaiso during the March 3, 1985 earthquake. All these buildings developed shear behavior during this event, as shown by their cracking patterns.

CONCLUSIONS

The most relevant conclusions of this study may be summarized as follows:

1. An analytical model to predict the inelastic seismic response of reinforced concrete, shear wall buildings, has been developed. This model allows the development of a flexural mode of failure or a shear mode of failure in the wall elements, and is able to predict the collapse of the structure.

2. The flexural mode of failure model is standard. The shear mode of failure model has been developed using experimental results of cyclic test of both squat shear walls and beams failing in shear.

3. Results obtained with this model are promising. This will permit to carry future studies to ascertain the structural characteristics of shear wall systems in order to achieve an acceptable behavior during severe earthquakes.

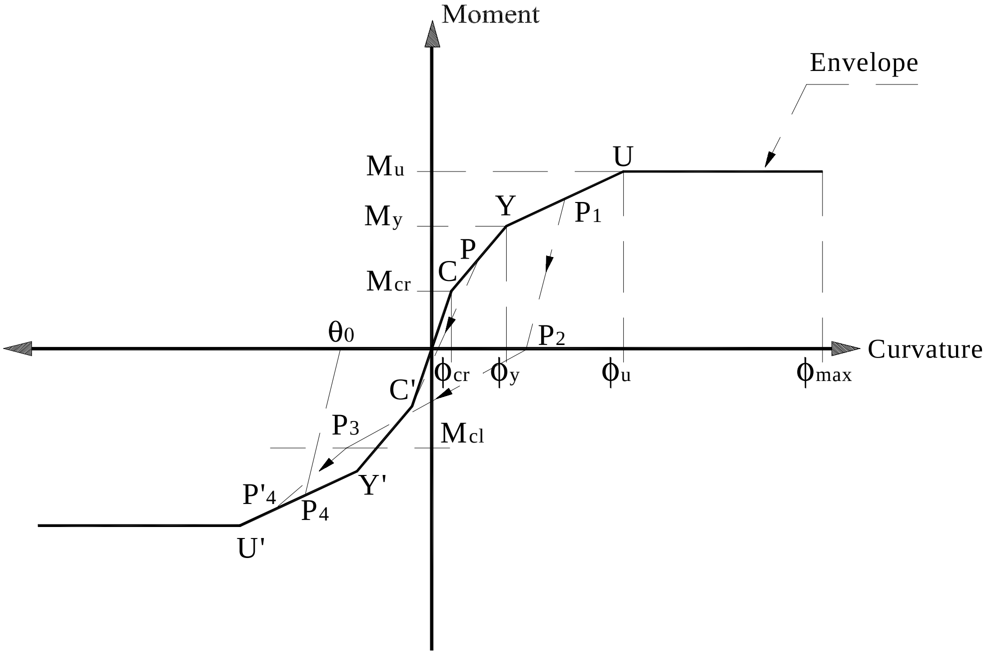


Figure 1: Hysteretic model for flexural mode of failure (beams, columns, shear walls).

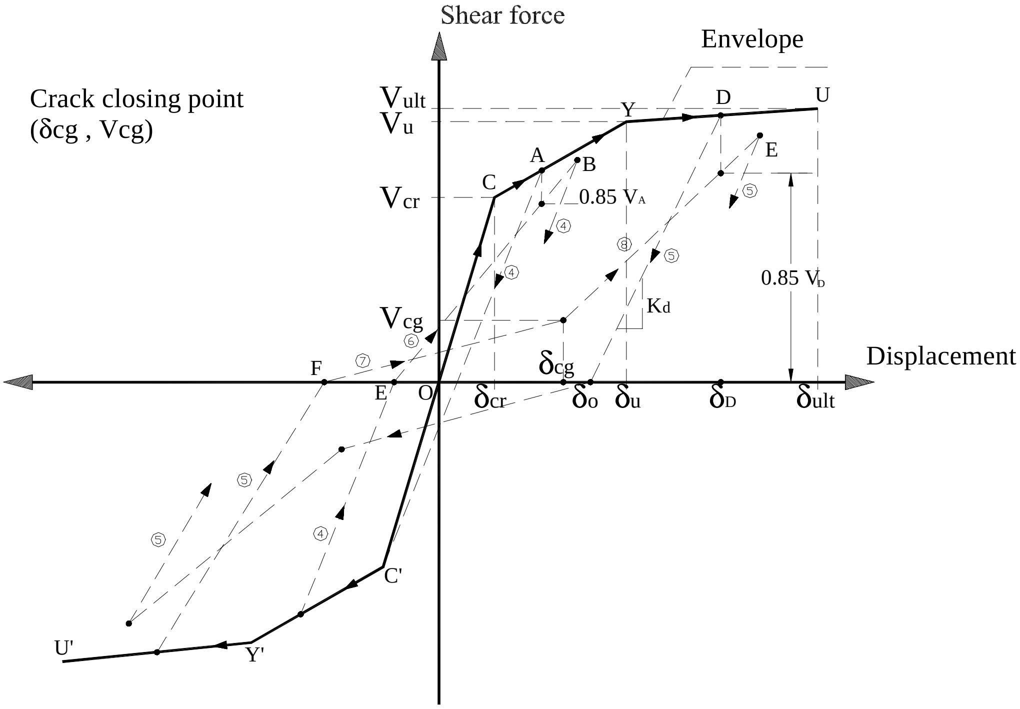
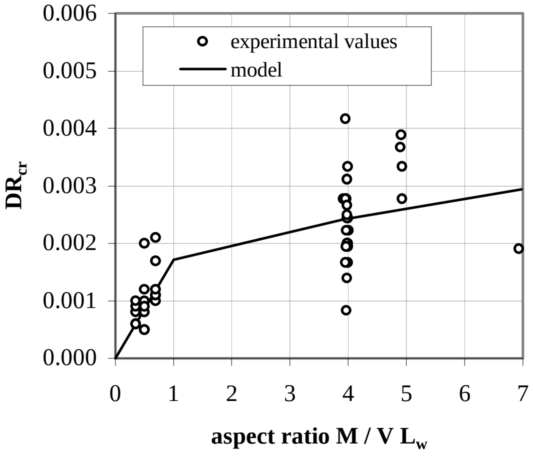


Figure 2: Hysteretic model for shear mode of failure (shear walls).



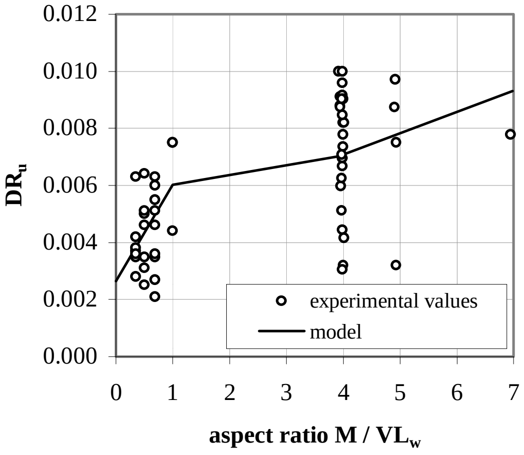
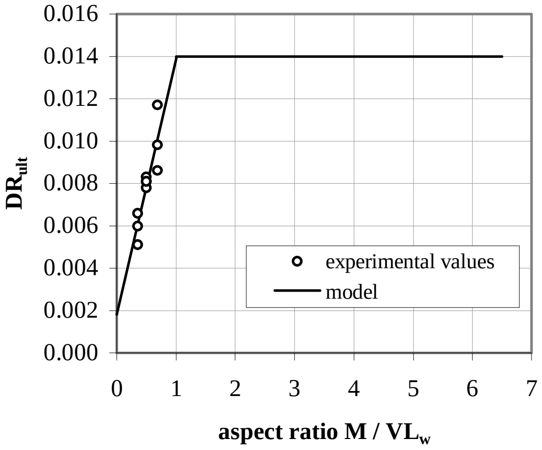
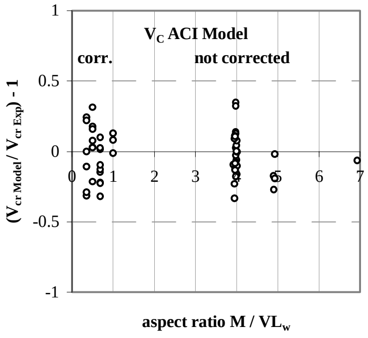


Figure 3: Shear model to estimate drift **Figure 4: Shear model to estimate**



at first cracking. **drift at maximum strength.**

Figure 5: Shear model to estimate drift at ultimate strength.



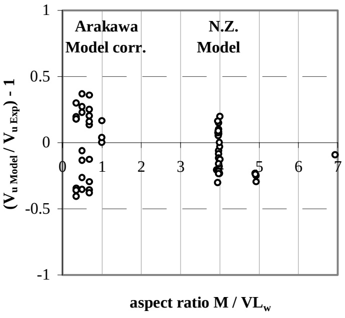


Figure 6: Comparison of shear model to estimate ***Figure 7: Comparison of shear model to estimate***

cracking strength with experimental values. **maximum strength with experimental values.**

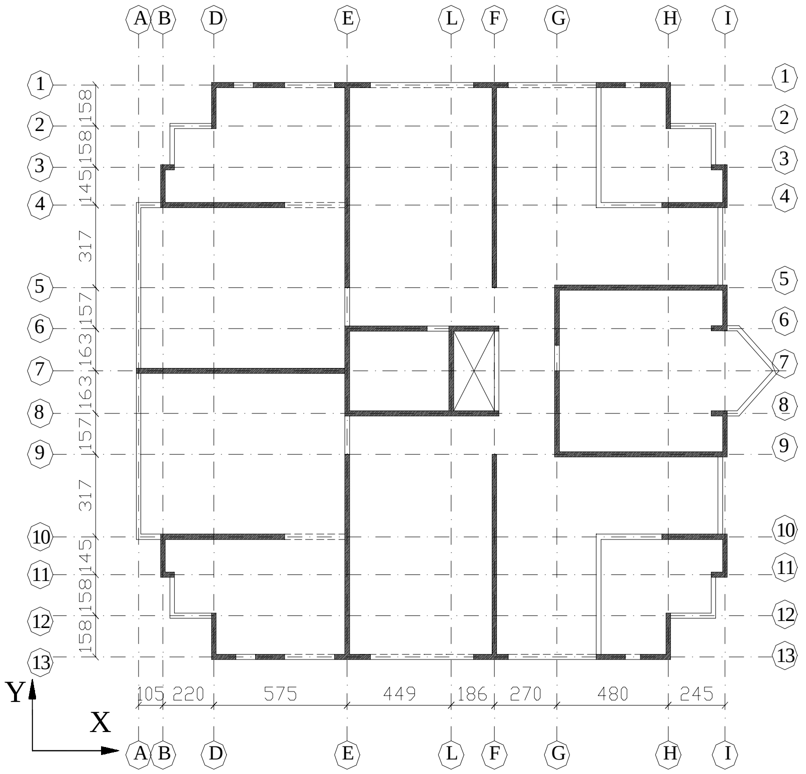


Figure 8: Structural plan Building Nº2. (Dimensions in centimeters).

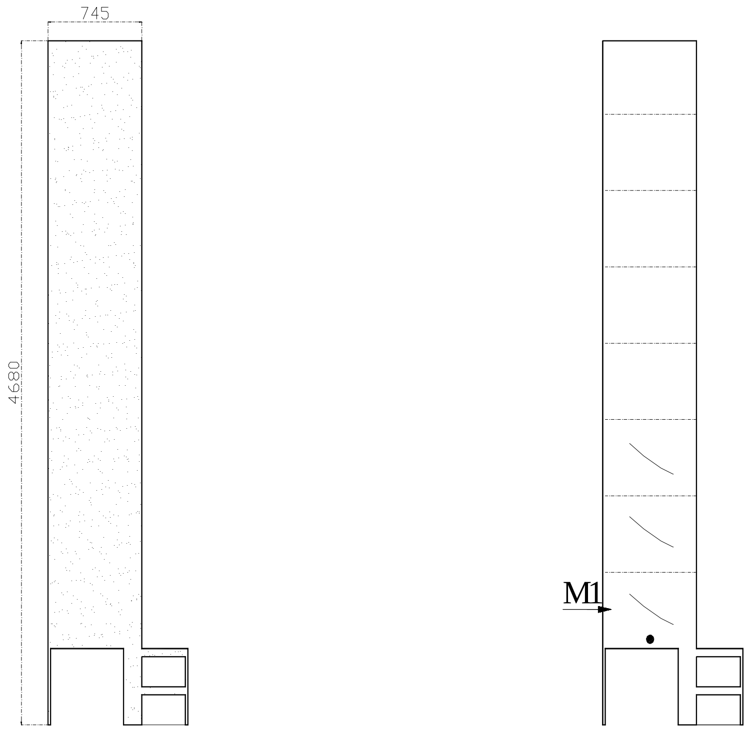


Figure 9: Plastic hinge and shear cracks at t=32 sec. in shear walls, axes 5 and 9,

X-direction earthquake, Llolleo record. (Dimensions in centimeters).

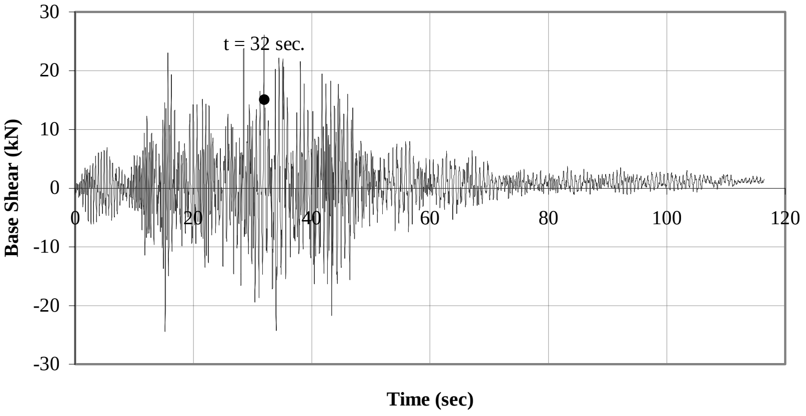


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Figure 10: Base shear Building Nº2, X-direction earthquake, Llolleo record.

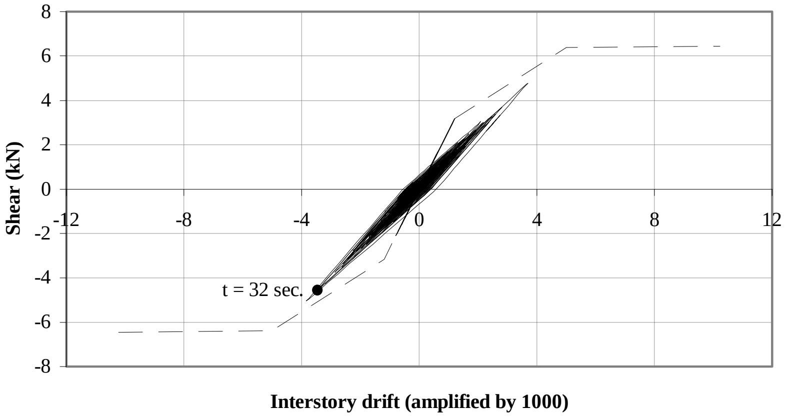

Figure 11: Hysteretic shear behavior wall M1, axes 5 and 9.

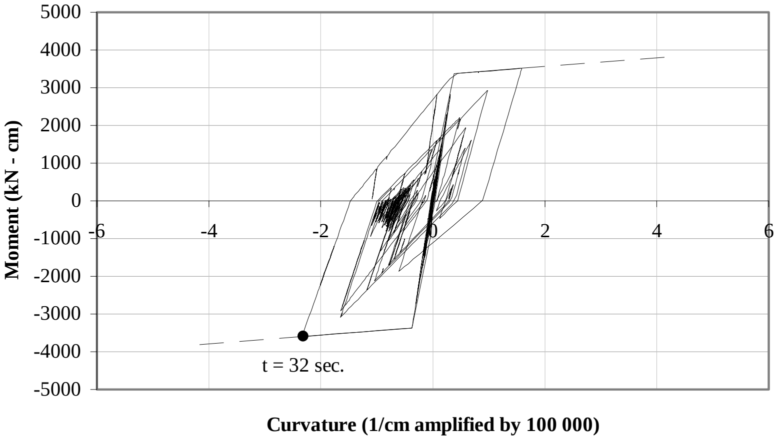

Figure 12: Hysteretic flexural behavior at base of wall M1, axes 5 and 9